Metrology requirements of future x-ray telescopes

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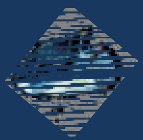
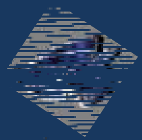
Astronomical x-ray telescopes need large area and high-resolution imaging.

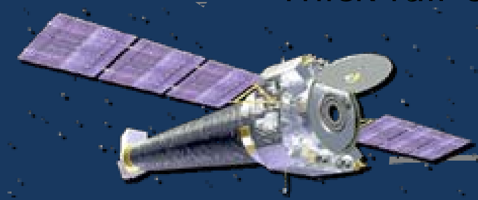


Einstein Observatory (HEAO-2)
1978-1981 ($f = 3.3$ m, $A = 0.04\ m^2$) 10″
Thick full-cylinder fused-quartz mirrors

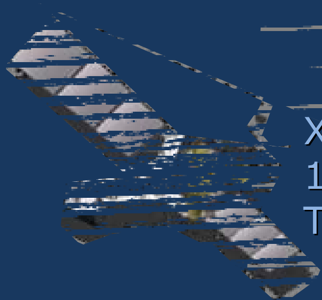
International X-ray Observatory (IXO)
≈2022 ($f \approx 20$ m, $A \approx 4\ m^2$) 5″
Thin segmented mirrors
(glass or silicon-pore)



Röntgen Satellit (ROSAT)
1990-1999 ($f = 2.4$ m , $A = 0.10\ m^2$) 5″
Thick full-cylinder glassy-ceramic mirrors



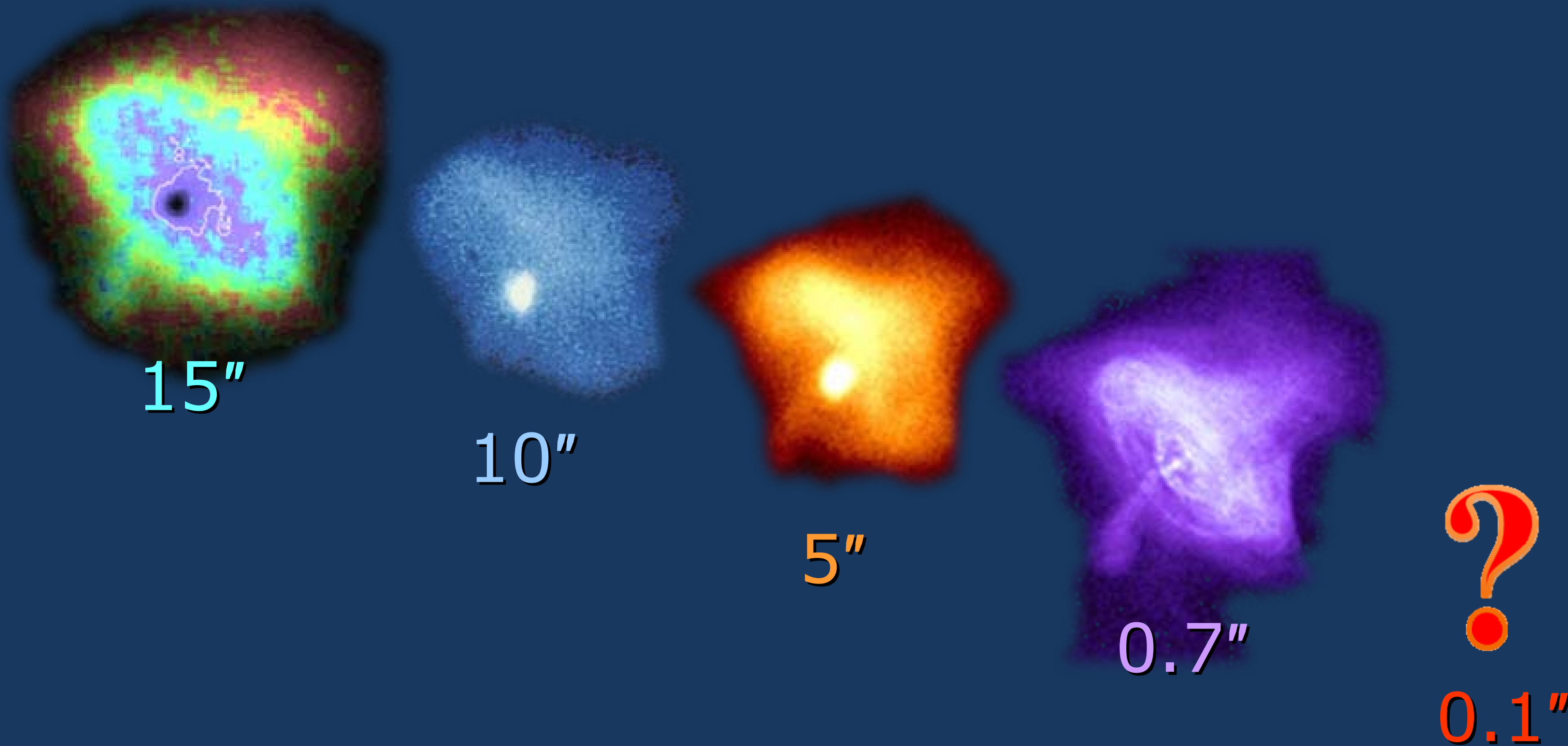
Chandra X-ray Observatory
1999-? ($f = 10$ m, , $A = 0.11\ m^2$) 0.7″
Thick full-cylinder glassy-ceramic mirrors



XMM-Newton
1999-? ($f = 7.5$ m, $A = 0.5\ m^2$) 14″
Thin full-cylinder electroformed-nickel mirrors

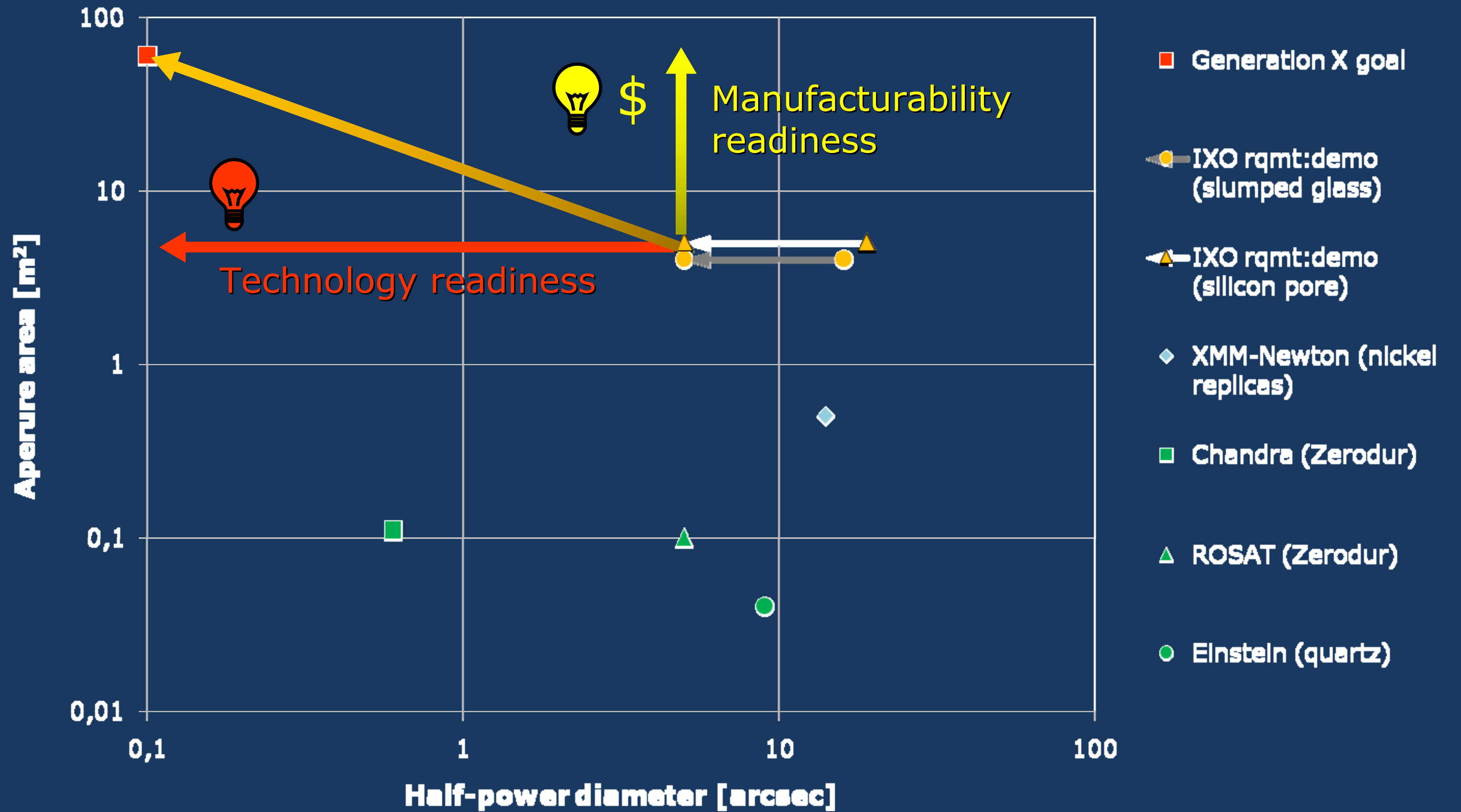
Generation X
2035+ ($f \approx 50$ m, $A \approx 60\ m^2$) 0.1″
Thin segmented (glass) mirrors

Higher resolution improves both imaging quality and sensitivity (noise reduction).



Aperture area improves sensitivity (signal increase), down to the confusion limit.

In principle, segmented optics may be scalable to arbitrarily large areas.



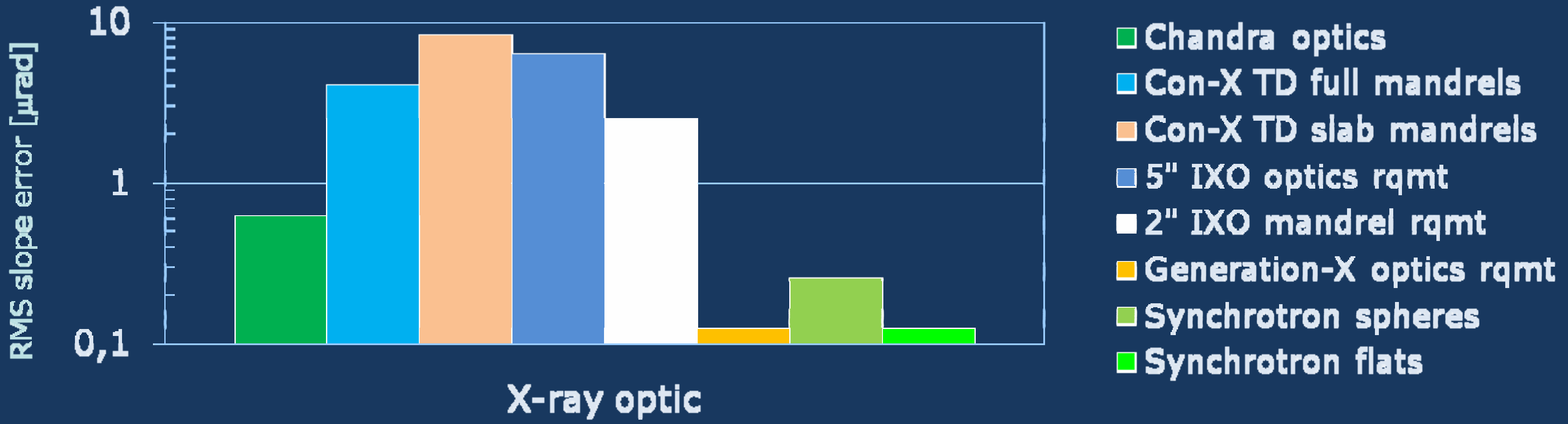
There are 4 top-level terms in the error budget for 0.1″ HPD (0.074″ RMS blur)

- Mirror surface quality
  - Microroughness scatters far outside 0.1″ ∅.
  - Slope deviations < 0.026″ = 0.125 μrad RMS.
- Mirror mounting
  - Mount must not distort mirror, or
  - Must be able to correct any distortions.
- Mirror-pair (P–S) alignment
  - Accuracy of P–S slope difference < 0.037″ RMS.
- Positioning of aligned mirror pairs
  - Accuracy of co-location < $0.36\mu\times F$ RMS.
    - P–S pairs are not sensitive to overall tilt errors.

There are alternative approaches for addressing each error contribution.

- Mirror surface quality
  - Replicate to requirements at >mid-f.
  - Correct >mid-f figure of replica (in situ).
- Mirror mounting
  - Align very stiff mirrors with correct low-f figure.
  - Actively correct low-f figure of flexible mirrors.
- Mirror-pair (P–S) alignment
  - Align separate P and S replicated mirrors.
  - Replicate integral P+S mirror from mandrel.
- Positioning
  - May need rigid-body adjustment on-orbit.

Requirement on axial-slope deviation is near state-of-art, even for thick mirrors.



Metrology needs of future x-ray telescopes (e.g. Generation X):

- Axial-slope deviations along meridians
  - Verify < 0.125 μradian (RMS) at ≈ 0.025 μradian accuracy.
  - Measure mirror segments about 1-m long.
- Meridian-to-meridian mean-slope (cone-angle) variations
  - Verify mounted S-P differences < 0.175 μradian (RMS).
  - Sample azimuthal spans about 1-m wide and 1-6 m radius.

Programmatic constraints require innovation for manufacturing readiness.

- Optimize mandrel fabrication and replication.
  - Minimize post-replication corrections.
- Automate all processes as fully as possible.
  - Implement closed-loop fabrication & metrology.

10000 m^2
0.1-μrad (RMS)
mirror surfaces

Mass constraint
Total mirror mass
≤ 10 tonne

Mirror areal density
≤ 1 kg/m^2

Monetary constraint
Total mirror cost
≤ 0.5 G$

Mirror areal cost
≤ 50 k$/$m^2$

Schedule constraint
Mirror fabrication time
≤ 4 years

Production rate
≥ 8 m^2/day

Summary

- Fundamental needs for future x-ray telescopes
  - Sharp images ⇒ excellent angular resolution.
  - High throughput ⇒ large aperture areas.
- Generation-X optics technical challenges
  - High resolution ⇒ precision mirrors & alignment.
  - Large apertures ⇒ lots of lightweight mirrors.
- Innovation needed for technical readiness
  - 4 top-level error terms contribute to image size.
  - There are approaches to controlling those errors.
- Innovation needed for manufacturing readiness
  - Programmatic issues are at least as severe.